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AN APPROXIMATE DETERMINATION OF THE POWER REQUIRED TO MOVE CONTROL SURFACES AS RELATED TO CONTROL-BOOSTER DESIGN

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AN APPROXIMATE DETERMINATION OF THE POWER REQUIRED TO MOVE CONTROL SURFACES AS RELATED TO CONTROL-BOOSTER DESIGN

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SUMMARY

As a part of a general investigation of control boosters, preliminary calculations were made to indicate the sizes of control boosters necessary to move the controls of airplanes of various sizes. The analysis was based on the assumption that the controls were moved with a rapidity and amplitude equal to that measured with a fighter airplane in simulated combat. A corollary purpose consisted in determining the effect on reducing booster-power unit size of incorporating an energy accumulator in the booster system.

The analysis indicates that up to 13 times as large a power unit would be required for supplying sudden bursts of power if no accumulated energy were available as compared to a power unit capable of supplying the average power used in continuous maneuvering in combination with a relatively small energy accumulator. Results of the calculations show that to operate all the controls of a small fighter-type airplane, a power source of 0.057 horsepower in combination with an accumulator capable of storing 51.4 foot-pounds of energy would be sufficiently large if friction and booster cycle losses are nelgected. In this case, the accumulator would be required to supply bursts of power in amounts up to 0.462 horsepower for extremely short periods of operation. The power requirements and booster sizes increase rapidly with airplane size. Under the assumptions of the analysis, a power source of 2.05 horsepower in combination with an accumulator capable of storing 3350 foot-pounds of energy would be required to operate all the controls of a bomber weighing about 70,700 pounds. In this case, the peak-power demand required from the accumulator would approximate 20 horsepower. Some of the problems involved in predicting the booster requirements are discussed in relation to the assumptions that were made in the

preliminary evaluation. It is concluded that extensive flight tests are required to determine the effects of speed, size, and airplane functional type on the booster requirements.

INTRODUCTION

A general investigation of control boosters is being conducted at the Langley Laboratory of the NACA in an effort to provide some of the information needed for their design. The investigation is divided into the following four phases:

(1) Study of flight tests and hinge-moment data to determine the speed with which the controls are usually moved and the power required of a booster system to move them with the desired rapidity.

(2) Analysis of booster systems in use or in the design stage.

(3) Wind-tunnel and ground tests of the more promising booster systems.

(4) Flight tests of airplanes equipped with booster controls.

This paper is a contribution to the first phase of the general investigation.

SYMBOLS

ΔE increment of energy required to drive controls

H_B hinge moment on control surface at beginning of incremental-control motion during which control is moved at constant rate

H_E hinge moment on control surface at end of incremental-control motion during which control is moved at constant rate

$\Delta\delta$ increment of control-surface deflection in control motion during which control is moved at constant rate

δ_{TR_B} control deflection from trim at beginning of incremental-control movement

δ_{TR_E} control deflection from trim at end of incremental-control movement

$\delta_{TR_{av}}$ average control deflection from trim for incremental-control movement

$\delta_{a_{TR}}$ aileron deflection from trim

$\overline{\delta}^2$ energy factor, degrees^2

$\overline{\delta}_a{}^2$ aileron energy factor, degrees^2

$\overline{\delta}^2/t$ power factor, degrees^2 per second

t time, seconds

$K = \left(\frac{dC_h}{d\delta}\right)_T$

$\left(\frac{dC_h}{d\delta}\right)_T$ total rate of change of hinge-moment coefficient with control-surface deflection, per degree (includes effect of rate of change of hinge-moment coefficient with change in angle of attack)

$\frac{dC_h}{d\delta}$ rate of change of hinge-moment coefficient with change in control-surface angle, per degree

$\frac{dC_h}{d\alpha}$ rate of change of hinge-moment coefficient with change in angle of attack, per degree

S control-surface area back of hinge center line, square feet

$\overline{c}$ root-mean-square chord of control surface back of hinge center line, feet

q_c impact pressure, pounds per square foot

$\frac{d\delta_e}{d\alpha_t}$ rate of change of elevator angle with change in angle of attack at the horizontal tail

$\Delta\delta_{a_T}$ incremental change in total aileron angle (sum of upgoing and downgoing aileron movements)

METHOD OF ANALYSIS AND GENERAL RESULTS

Three essential elements are used in a normal control-booster system: (1) the power unit, which supplies energy to the booster system; (2) the accumulator, which stores up a certain quantity of energy that is instantly available on demand; and (3) the booster unit, which takes energy either from the power unit or accumulator and drives the control surface. The function of the accumulator is to take care of short-period demands for great amounts of power. The purpose of the accumulator is to reduce materially the necessary size of the power-input unit. The present problem consists in finding the relation between the sizes of the power unit and accumulator that will always satisfy the energy demands involved in moving the controls of an airplane having any given physical dimensions. The results obtained should be applicable to any type of control-booster system, whether hydraulically, electrically, mechanically, or air driven.

An analysis was made by selecting an actual variation of airplane control motion with time and assuming that this variation is applicable to the general case for purposes of computing control energy and power requirements. From a considerable quantity of records available for a highly maneuverable fighter airplane in simulated combat, approximately 25 seconds of typically violent maneuvering were selected. Figure 1 is a reproduction of the selected time history of airplane and control motion.

If it is assumed that hinge-moment variations with control deflection are linear and aerodynamic damping of the controls is neglected, a plot may be constructed from the data in figure 1 of the time variation of some quantity that is proportional to the energy used in deflecting the controls. Under the preceding assumptions, the energy required to deflect the control surface through a given angle may be determined as the average of the hinge moments acting on the surface at the beginning and end of the motion multiplied by the change in control-surface angle; that is,

$$\Delta E = \frac{H_B + H_E}{2} \Delta\delta$$

Since the hinge moment is proportional to the control-surface angle, the energy will be proportional to the average of the control-surface angles at the beginning and end of the motion multiplied by the change in control-surface angle, or

$$\Delta E \propto \frac{\delta_{TR_B} + \delta_{TR_E}}{2} \Delta\delta = \delta_{TR_{av}} \Delta\delta$$

Figure 2 gives the results obtained by summing up the incremental-energy quantities required to drive the aileron control in the maneuver of figure 1. The energy has been expressed in terms of an energy factor $\overline{\delta}^2$, which represents the summation of average control deflection from trim times incremental control deflection over which the rate of control motion was approximately constant:

$$\overline{\delta}^2 = \sum_{0}^{t} \delta_{TR_{av}} \Delta\delta$$

The time history was broken into increments during which the rate of control motion was approximately constant in order to determine the variation of the control power input with time. The variation during the maneuver of control power input with time affects the balance between power unit and accumulator sizes. Inasmuch as energy to move the controls is required only when the control is moved away from trim, the numerous flat spots in the curve represent conditions where the controls were either fixed or were returning toward trim. The energy factor plotted in figure 2 may be converted into energy in units of foot-pounds by use of the relation

$$\text{Work} = \overline{\delta}^2 \frac{K}{57.3} S\overline{c}q_c \qquad (1)$$

Values of K to be used in equation (1) are the total hinge-moment-coefficient variation for the control surface, which includes the variation of hinge-moment coefficient with angle of attack. Thus, the response characteristics of any particular airplane to which the selected variation of control motion is applied are accounted for in the equation.

Figure 2 and similar plots for the other two controls were used directly to establish general relations between the power input required and the accumulator capacity necessary to supply every energy demand of the controls. Under the assumption that energy is supplied to the accumulator at a given rate whenever its energy content falls below its rated capacity, a simple trial and error graphical solution was employed to determine the desired relation. This solution consisted in finding, for various assumed energy capacities, the line with the smallest slope (smallest power-input rating) that would provide an energy-available curve which would just meet the energy-required curve at the most critical time. One such trial and error solution for an accumulator capacity factor of 200 degrees^2 is shown in figure 2. Note that the slope $\overline{\delta}^2/t$ so determined is a direct measure of a minimum power-input factor which, in combination with the assumed energy capacity, will satisfy the energy demands of the control throughout the entire 25-second maneuver. Just as in the case of energy, the power factor may be converted into power in foot-pounds per second by use of equation (1) with the power factor $\overline{\delta}^2/t$ in place of the energy factor $\overline{\delta}^2$.

$$\text{Power} = \frac{\overline{\delta}^2}{t} \frac{K}{57.3} S\overline{c}q_c \qquad (2)$$

Results showing the balance between power input and accumulator capacity required for performing 25-second periods of violent maneuvering at widely spaced intervals are given in figure 3 for all three controls. Attention is directed to the horizontal line labelled "Indefinite maneuvers" in this figure. This line defines the average rate at which, by far, most of the energy required to move the controls was used and is therefore representative of the minimum power input required for indefinite maneuvering. A determination of this value for the aileron control is given by the slope of the dashed line in figure 2. Figure 3 shows the isolated maximum power values plotted for accumulator capacities of zero. These points were determined from figure 2 and other similar plots by measuring the greatest rate of energy output required to drive the controls at any time during the selected maneuver.

The data of figure 3 indicate that up to 13 times as large a power unit would have to be provided if no accumulator were used as compared to the minimum power-

unit rating required for indefinite maneuvering in combination with a relatively small accumulator. In this connection, it is believed that a combination consisting of an extremely small power unit and a very large accumulator would not be considered since this combination would be satisfactory only for limited-duration maneuvers occurring at widely separated times. Probably the best all-around combination would be one in which the power unit is the smallest required for indefinite maneuvering together with an accumulator of moderate size.

APPLICATION TO SPECIFIC AIRPLANES AND DISCUSSION

In order to gain some idea of the sizes of power units and accumulators necessary to supply 100 percent of the energy required to move the controls of airplanes of various sizes with a rapidity equal to that attained with the fighter airplane used in the selected maneuver, the data of figure 3 and equation (1) have been applied with appropriate dimensions to four airplanes covering the range of size of present interest. These calculations were made for the minimum-size booster combinations required for continuous maneuvering. Several assumptions apply to the results, which are shown in table I, as follows:

(1) All control surfaces are assumed to have no aerodynamic balance. This assumption leads to approximate values of $\frac{\partial C_h}{\partial \delta}$ of -0.010 per degree and of $\frac{\partial C_h}{\partial \alpha}$ of -0.003 per degree for surfaces of usual dimensions.

(2) All airplanes are assumed to have a degree of stick-fixed longitudinal stability such that $\frac{d\delta_e}{d\alpha_t} = 1.0$. This assumption leads to a value of K for the elevator of 0.007 per degree.

(3) All maneuvers are accomplished with zero sideslip angle. This assumption results in a value of K for the rudder of 0.010 per degree.

(4) The effect of change in angle of attack over the ailerons on aileron hinge moments during rolling is neglected. This assumption results in a value of K for the ailerons of 0.010 per degree.

(5) The indicated airspeed is constant at 175 miles per hour. This condition was very nearly the case in the selected maneuver of the fighter airplane.

(6) All transfers of energy in the control-booster system are accomplished at 100-percent efficiency for purposes of this analysis.

Some of the foregoing assumptions are related directly to certain basic control-booster considerations, some of which are discussed in the following paragraphs.

In practice some aerodynamic balance would probably be used on control surfaces as a means of reducing the size and weight of the booster. In these cases, the booster requirements would be expected to very inversely with the degree of aerodynamic balance employed (as expressed by the factor K in equation (1)); however, the power required to overcome control-system inertia in order to obtain the desired quickness of response will probably determine the minimum size of booster that can be used when the controls are closely balanced aerodynamically. No account was taken of control-system inertia in the illustrative calculations, the results of which are given in table I.

Although the illustrative calculations for booster size were made for only one speed, the booster power required is undoubtedly dependent on the speed of flight. Consider, for instance, the control-power requirements for a fighter airplane in a particularly violent type of evasive maneuver. Assume that a pilot rolls an airplane from 90° bank in one direction to 90° bank in the other direction by use of full aileron control and sufficient rudder deflection to maintain zero sideslip at all times; assume also that the elevator control is used to produce the pilots' limit load factor when the airplane is banked 90° and 1g normal acceleration at the instant the airplane passes through laterally level flight. Finally, assume the maneuver is repeated continuously (without pause when the plane reaches 90° bank in either direction). Under these conditions, the power necessary to move the ailerons should vary approximately as the cube of the indicated airspeed, that necessary to move the rudder as the first power of the indicated airspeed, and that necessary to move the elevator as the inverse of the indicated airspeed (at constant altitude). This analysis neglects, of course, the possible adverse effects

of compressibility on the control forces of airplanes flown in the critical-speed region. Although the use of a booster might considerably alleviate control problems at extreme speeds, no attempt to analyze quantitatively the requirements of a booster system in this regard seems possible until more complete data on the aerodynamic effects are available.

The effect of airplane size, as related to the rate of response to control deflection, must also be considered in any accurate analysis of booster requirements. For purposes of the illustrative calculations, all the airplanes were assumed to be subjected to the same variation in control motion with time. The shortcoming of this assumption can be shown by a simple analysis. For example, suppose a very large airplane, such as airplane D of table I, were to perform the evasion maneuver suggested above. If the rolling effectiveness of the ailerons were the same (in terms of wing-tip helix angle produced by full aileron deflection) as for the fighter indicated in table I (airplane A), the frequency of control motions for the large airplane would be reduced to about one-tenth the frequency of the control motions for the fighter because the length of time to roll to 90° would vary approximately as the ratio of the wing spans. The relative control power required would be reduced the same amount due to the slower response of the larger airplane. Obviously, then, it is not logical to assume that control-power requirements for airplanes of all sizes and types can be determined from any specific variation of control motion with time, or for that matter, from any specific type of spatial maneuver; for, whereas fighter airplanes encounter most violent maneuvering conditions in combat, very large airplanes may encounter most violent maneuvering conditions while flying through gusty air.

The preceding considerations serve to outline some of the major factors affecting booster requirements that could not be handled at the present time due to scarcity of appropriate flight data. It appears that extensive flight tests of various types of airplanes must be carried out if an accurate predetermination of the control-booster requirements of any projected design is to be made. Such tests would best be conducted with structurally sound airplanes equipped with overly large control boosters in order that the desired degree of maneuverability could always be achieved.

From the foregoing discussion the results obtained from the illustrative calculations for booster sizes (see table I) apparently cannot be regarded as accurate quantitative results. For the larger airplanes, particularly airplanes C and D, the estimates are liable to be in considerable error.

CONCLUDING REMARKS

An analysis of booster requirements presented has served to provide rough estimates of the sizes of boosters necessary for the continuous rapid maneuvering of airplanes of various sizes. Because a specific variation of control motion with time, taken from data obtained with a fighter airplane in mock combat, was applied to airplanes of different sizes and functional types, the results obtained are to be regarded as only rough indications of the power requirements. A further limitation of the calculations is that the variation in required control-booster power with speed of flight could not be taken into account although a theoretical analysis indicates speed of flight is one of the primary determinants of the required control-booster size. For a more accurate determination of control-booster requirements it appears that extensive flight tests must be made for airplanes of different sizes and functional types in order to determine the maneuvering conditions that are most critical with regard to the power required to operate controls.

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TABLE I

APPROXIMATE SPECIFICATIONS OF BOOSTER SYSTEMS REQUIRED FOR THE CONTINUOUS RAPID MANEUVERING OF AIRPLANES OF VARIOUS SIZES HAVING AERODYNAMICALLY UNBALANCED CONTROLS ASSUMING 100-PERCENT BOOSTER EFFICIENCY

				Ailerons			Rudder			Elevator			All controls		
Airplane	Wing span (ft)	Wing area (sq ft)	Normal gross weight (lb)	Power-unit rating required (hp)	Accumulator capacity required (ft-lb)	Peak power demand required from accumulator (hp)	Power-unit rating required (hp)	Accumulator capacity required (ft-lb)	Peak power demand required from accumulator (hp)	Power-unit rating required (hp)	Accumulator capacity required (ft-lb)	Peak power demand required from accumulator (hp)	Power-unit rating required (hp)	Accumulator capacity required (ft-lb)	Peak power demand required from accumulator (hp)
A	34	213	7,850	0.017	16.8	0.103	0.024	46.7	0.152	0.016	27.8	0.207	0.057	51.4	0.462
B	65	602	28,500	0.081	78.5	0.491	0.111	215.0	0.702	0.102	179.2	1.320	0.295	472.7	2.513
C	149	2,780	70,700	0.45	430	2.72	0.60	1,152	3.80	1.01	1,768	13.07	2.05	3,350	19.59
D	320	11,500	300,000	3.39	3,280	20.55	7.55	14,580	47.8	9.31	16,320	120.5	20.25	34,180	188.8

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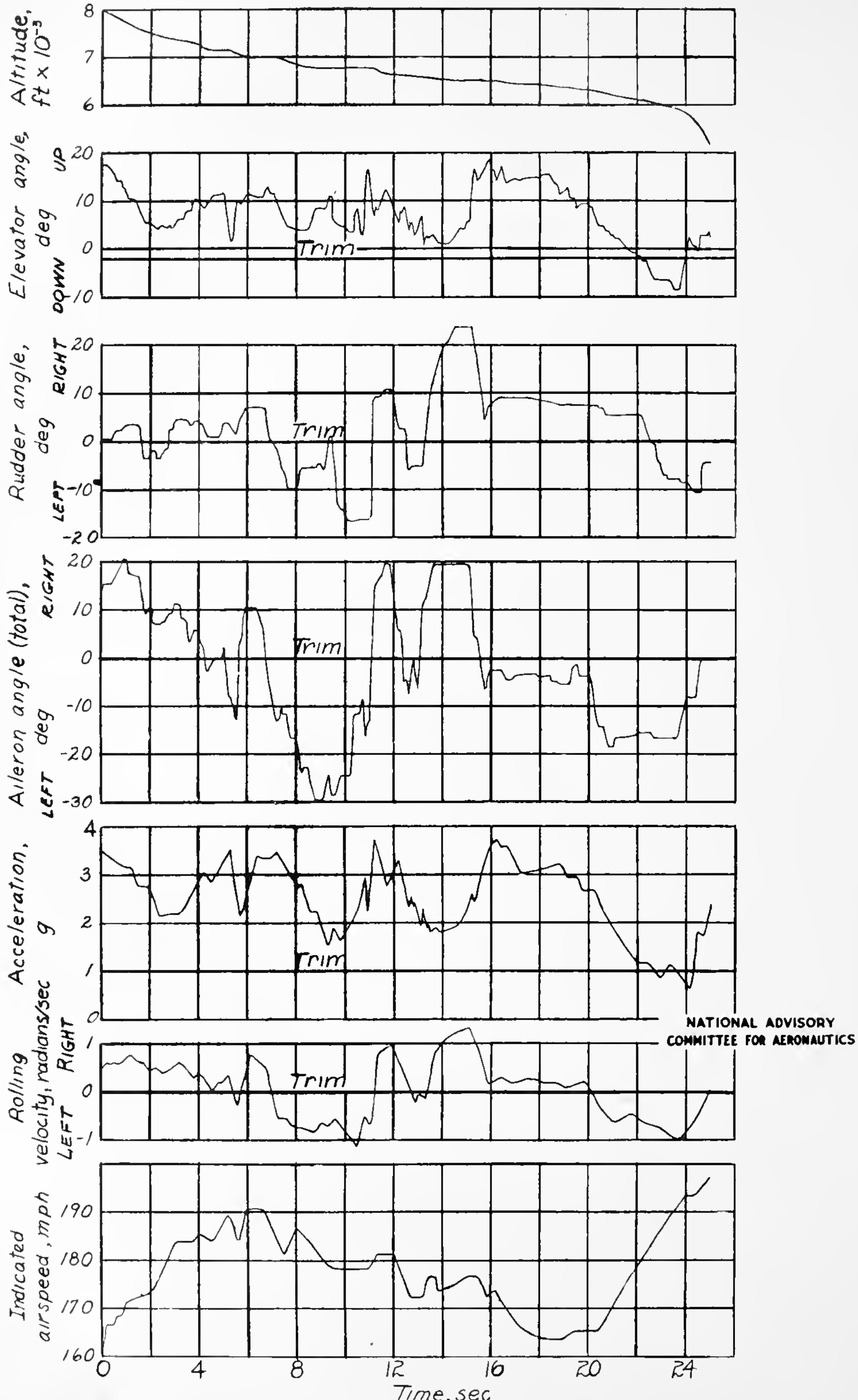


Figure 1. Time history of typical airplane and control motion of highly maneuverable fighter airplane in simulated combat.

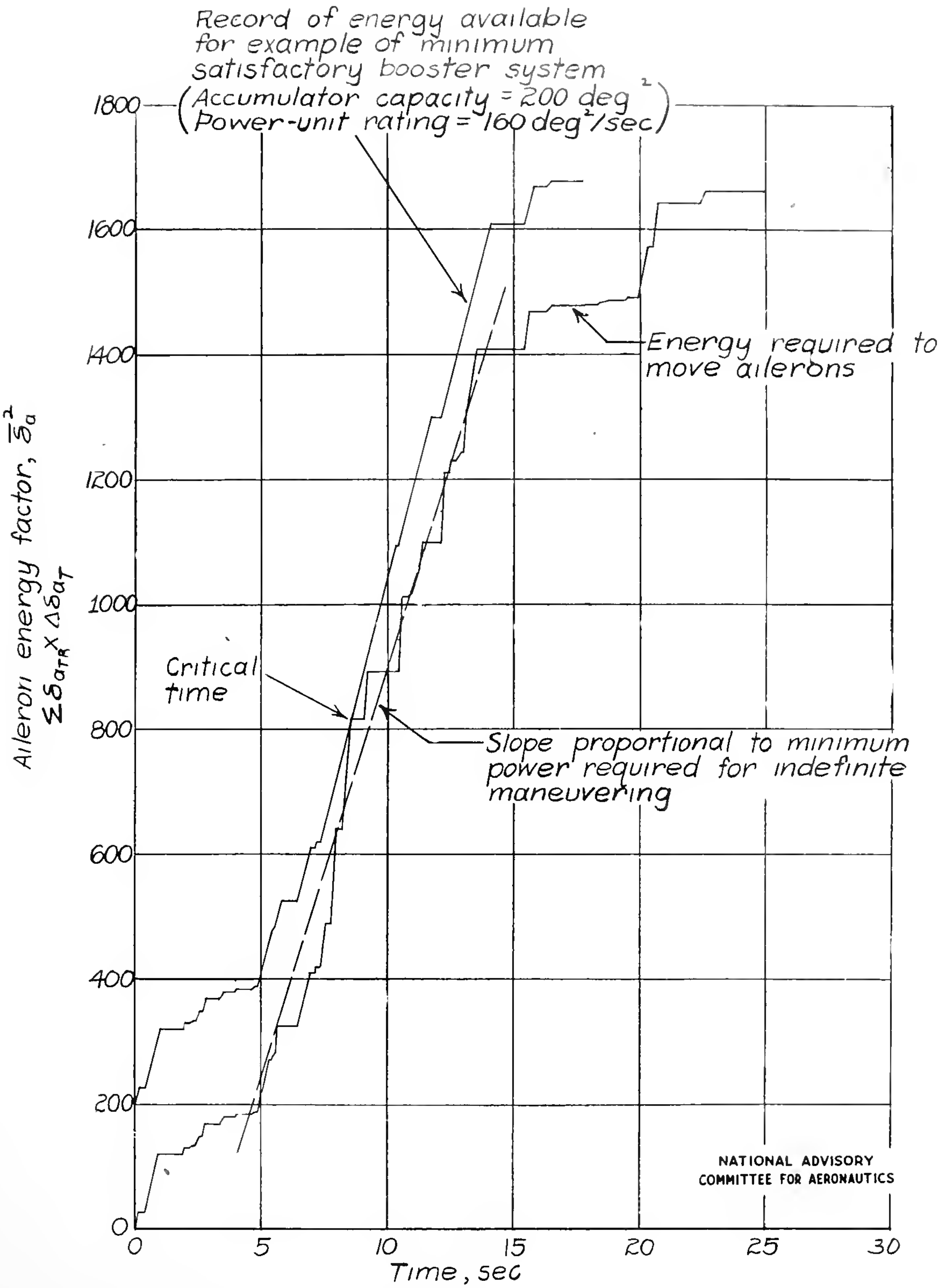
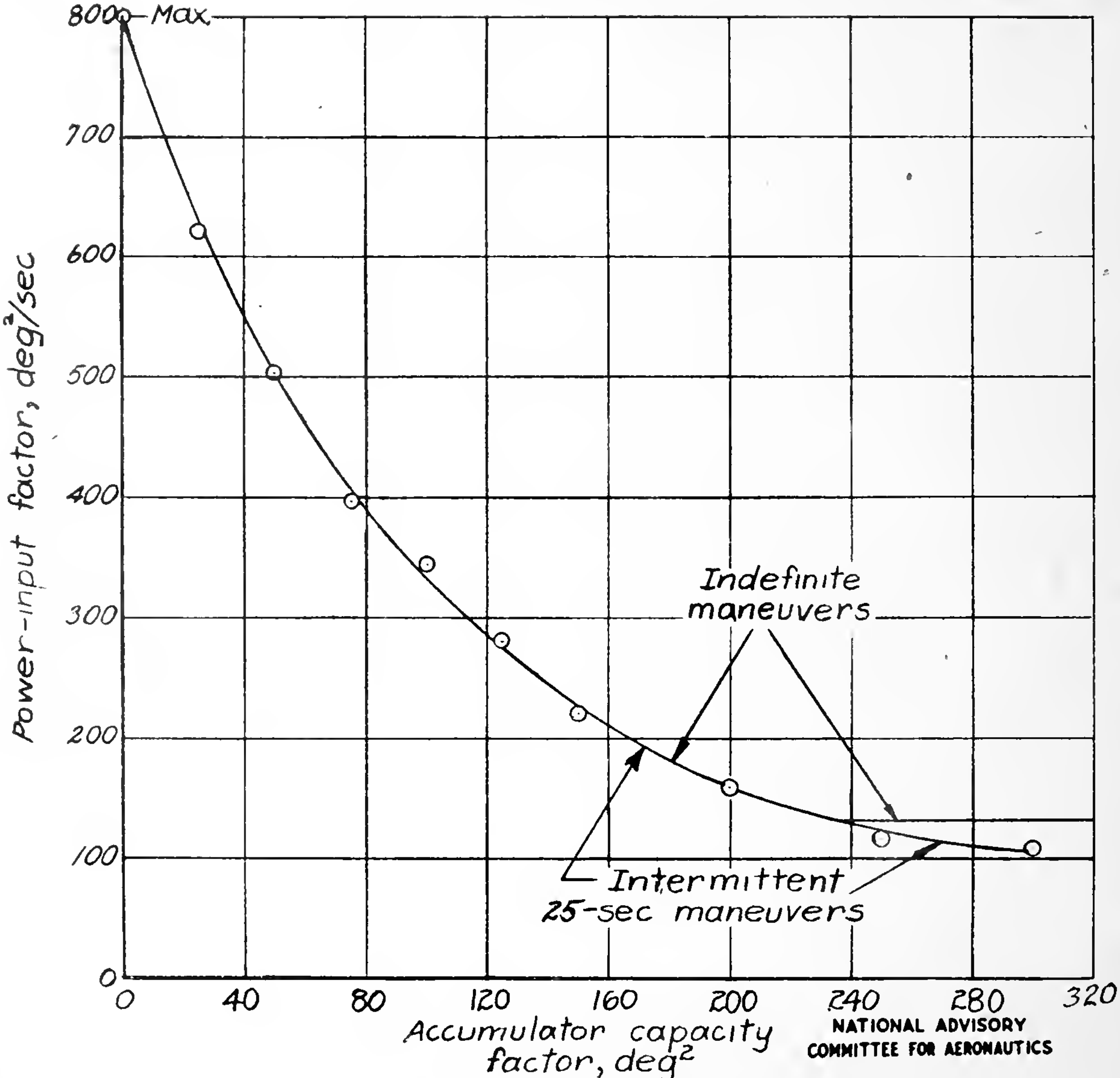
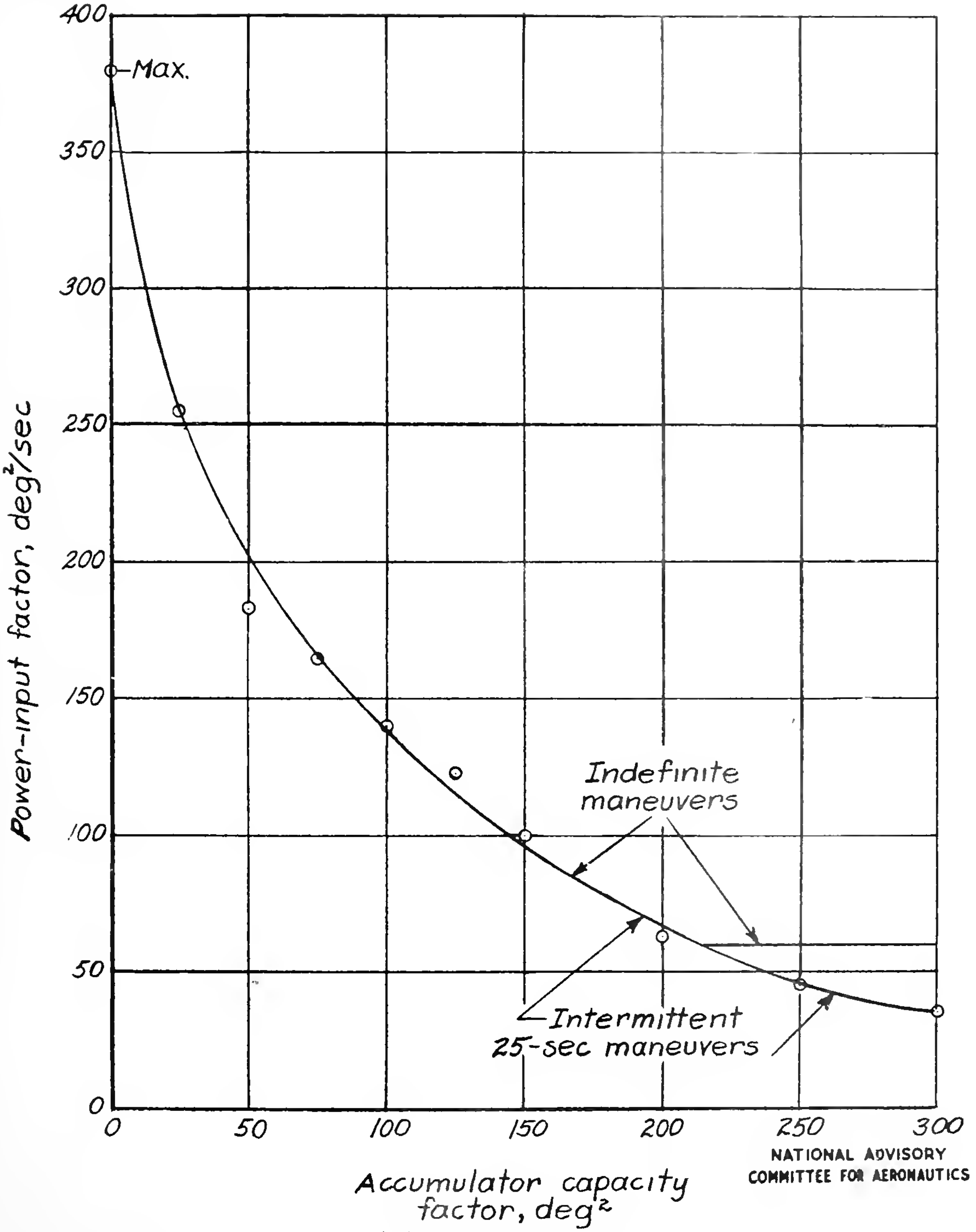


Figure 2.- Time record of the growth in energy factor required to move aileron control during maneuver shown in figure 1, assuming linear variation of aileron hinge moment with deflection from trim.



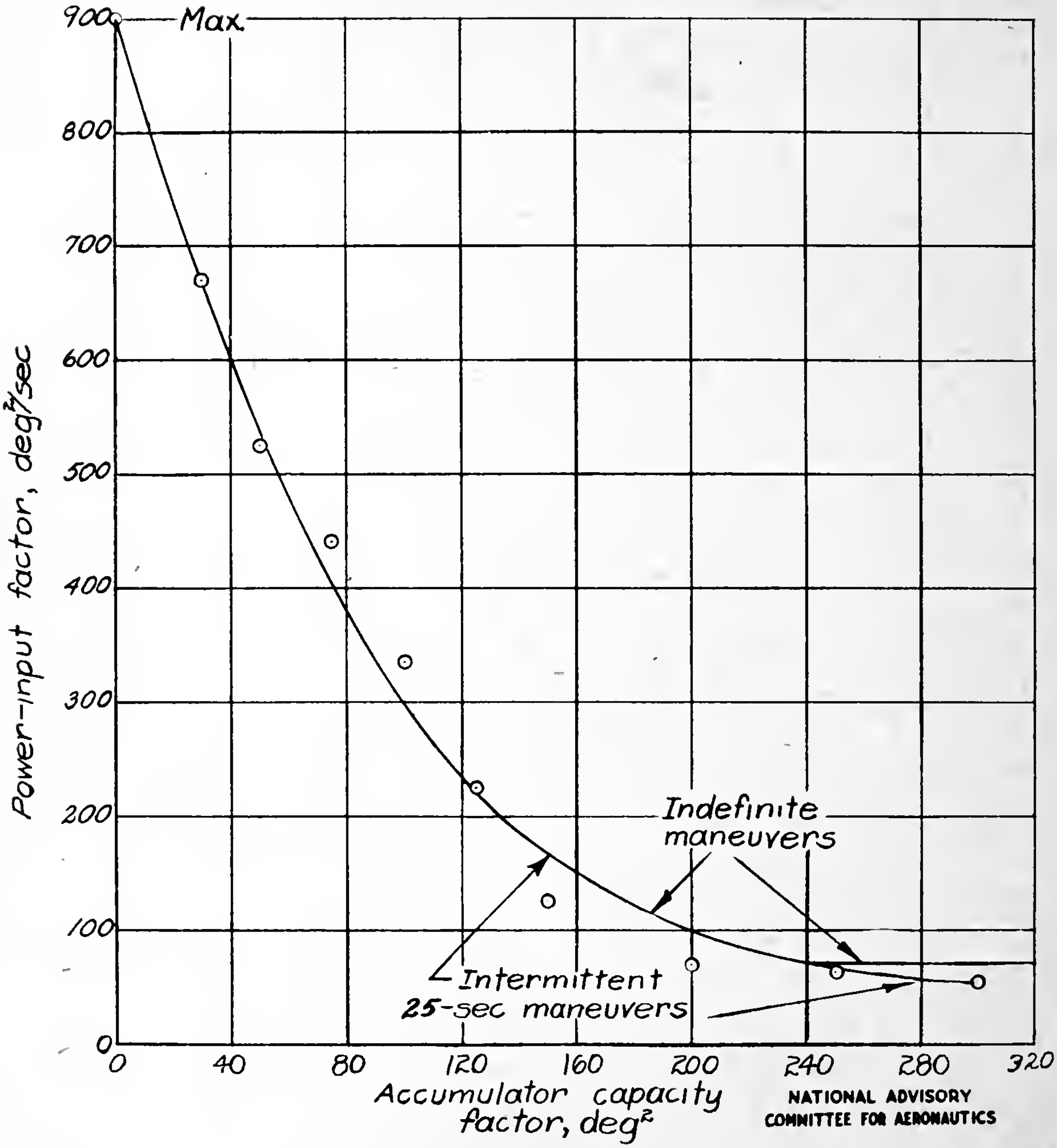
(a) Total aileron control.

Figure 3.- Relation between accumulator capacity factor and power-input factor required to move controls during violent maneuvers as determined from records of a fighter airplane in simulated combat.



(b) Rudder control.

Figure 3.- Continued.



(c) Elevator control.

Figure 3.- Concluded.